

AN ANALYSIS OF CO-AXIAL PULSE TRANSFORMERS*

by

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ABSTRACT

The basic idea of using a co-axial cable as an isolation pulse transformer for triggering spark gaps is not new.^{1,2,3,4,5} However, there are several distinct advantages of driving the braid as the primary as opposed to driving the inner conductor. The fundamental advantage is that the ratio of the output voltage to the input voltage is unaffected by the thickness of insulation between the inner conductor(s) and the braid. Thus, the transformer with the braid as the primary works well for isolating high secondary to primary voltages. This and other advantages are demonstrated.

Introduction

Figure 1 shows the co-axial transformer being considered as a one turn loop of co-axial cable. Figure 1 also shows what is meant by the terminology of "driving the braid as the primary (Case I)" and "driving the inner conductor as the primary (Case II)." The relative advantages of Case I over Case II are discussed in this paper.

Figure 2a shows the basic transformer circuit and Figs. 2b and 2c show the equivalent primary and secondary circuits, respectively. Of basic interest, is the voltage transfer ratio V_{out}/V_{in} when the trigger gap is open circuit (i.e. before the gap has broken down, $Z_{TG} = \infty$). It is desirable to have V_{out}/V_{in} as large as possible for reliable triggering. Table I gives the equations for the primary current $|I_p|$, the ratios of $|V_{out}/V_{in}|$ and $|\omega I_s/V_{in}|$, the normalized current in the trigger gap when the gap is short circuited (i.e. after the gap has broken down, $Z_{TG} = 0$).

The models in Fig. 2 are valid only for frequencies much less than the speed of light divided by the largest physical dimension of the transformer (i.e. the transformer must be much smaller than one wavelength). In actuality, the performance of the co-axial transmitter is not limited in this respect since transformers as large as a wavelength operate quite well. "Skin depth" effects, "proximity" effects and the electromagnetic radiation from the transformer acting as a magnetic dipole antenna have not been a problem.

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Table II gives the parameters of some of the transformers tested and the values of $|\omega I_S/V_{in}|$, which are about the same for either case. The nomenclature used in the table is defined in Figs. 1, 2, and 3. From Fig. 4 it can be seen that V_{out}/V_{in} is independent of D_{br}/D_{ic} for Case I but not for Case II. Thus, for Case I only, can one add as much insulation between the braid and the inner conductor as desired to isolate the secondary without affecting V_{out}/V_{in} . Hence, Case I works very well as a high voltage isolation transformer.

If one looks at a cross-section of one side of the transformer, it can intuitively be seen that all the flux generated by the current in the braid is external to the inner conductor. However, not all the flux generated by the current in the inner conductor is external to the braid (i.e. some of the generated flux is between the inner conductor and the braid). It is this difference that accounts for the results of Fig. 4. Theoretically, one can calculate (or use Ref. 6, p. 52) the inductance of a one turn loop with a major diameter D and a minor diameter D_{br} . This inductance is equal to L_{br} and equal to M because both inductances come from the same flux linkages. The inductance L_{ic} can be calculated for a one turn loop with a major diameter D and a minor diameter D_{ic} . Since D_{ic} is always less than D_{br} , L_{ic} must always be greater than L_{br} . The coefficient of coupling, k , can then be calculated from: $k = M/\sqrt{L_{br}L_{ic}}$. These calculations agree quite well with the experimental data in Table II. The fact that $L_{ic} > M$ and that $M = L_{br}$ accounts for the differences between the two cases in Fig. 4. It should be noted that in Fig. 3b for Case I ($Z_{TG} = \infty$), that the output voltage across kL_S is V_{in} but the input voltage is only kV_{in} which is less than V_{in} . This "apparent" voltage step-up between kL_P and kL_S is the result of the perfect coupling between kL_P and kL_S . These arguments, of course, neglect the flux in this cross-section that is generated by the currents flowing in the remainder of the transformer.

Adding extra insulation between the braid and the inner conductor also decreases the capacitance "C" (see Fig. 3) between the braid and the inner conductor. It is desirable to have this "C" as small as possible as it is a source for unwanted common mode noise. Thus, if Case I is used (see Fig. 4), one can make "C" as small as necessary to reduce the common mode noise by adding extra insulation without affecting V_{out}/V_{in} , the performance of the transformer.

Figure 5 shows one transformer ($D_{br}/D_{ic} = 21.3$) response to a square wave for Case I and Case II. One can see that for Case I, V_{out} is approximately V_{in} , but for Case II V_{out} is as indicated in Fig. 4. The "ringing" response of V_{out} has not caused problems in triggering spark gaps.

By "threading" one end of the inner conductor N times through the braid, one can obtain a 1: N step-up transformer. In order to prevent the turn to turn capacitance of the secondary from degrading the response, extra insulation must be added between the turns to decrease this capacitance. Neither the N secondary turns nor the extra insulation between them has a noticeable affect on the transformer coupling (i.e. $V_{out} = NV_{in}$ for $Z_{TG} = \infty$). The experimental evidence of this is not shown here, but the reasoning is the same as the explanation given for Fig. 4.

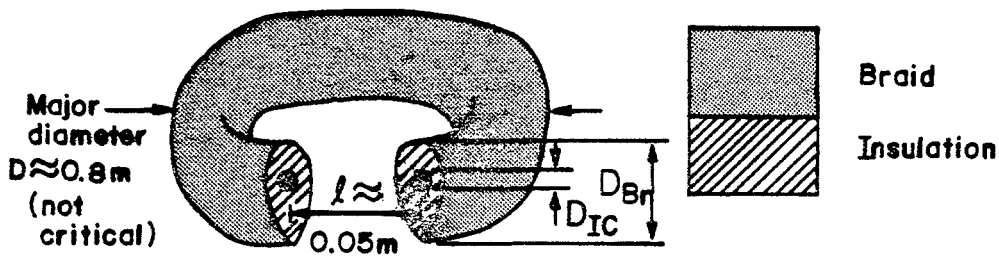
As an example, a 1:2 step-up transformer ($D \approx 0.40$ m, $D_{Br} \approx 0.03$ m, $l \approx 0.10$ m, inner insulation and conductor of RG-8/U coaxial cable with extra insulation) is presently being used to provide a 300 kV, 30 ns rise-time trigger to a rail gap for the TeePee 18 Theta Pinch from a 150 kV, 13 stage Marx bank. This step-up transformer was needed (1) to provide the high voltage trigger pulse required for reliable switching (2) to prevent damaging the Marx bank modules by isolating them from a reverse high energy common mode noise pulse of 75 kV when the rail gap was fired and (3) to break a ground loop.

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Case I: Driving the braid as the primary.

Case II: Driving the inner conductor as the primary.

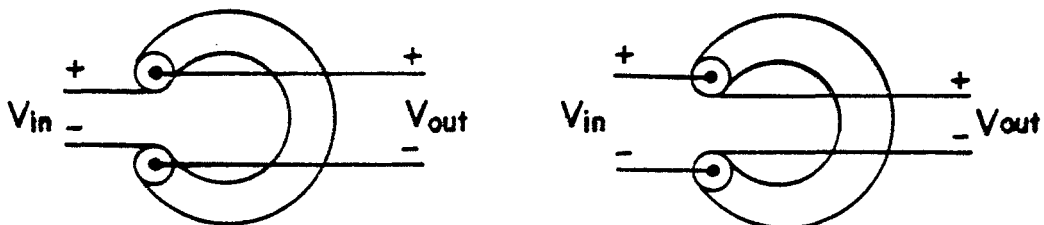
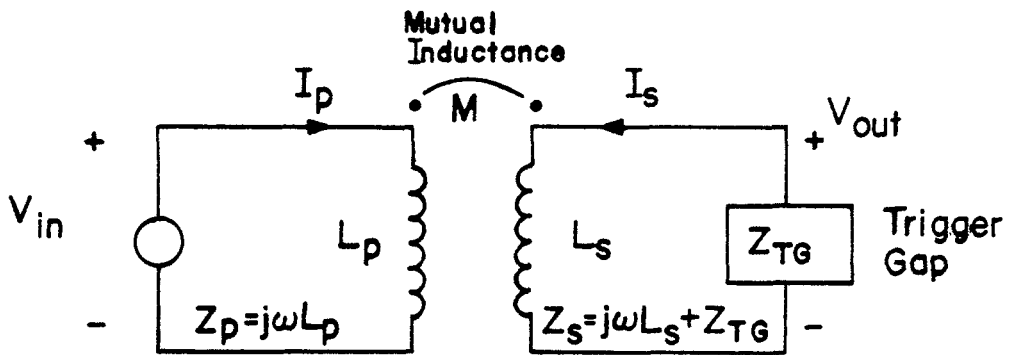
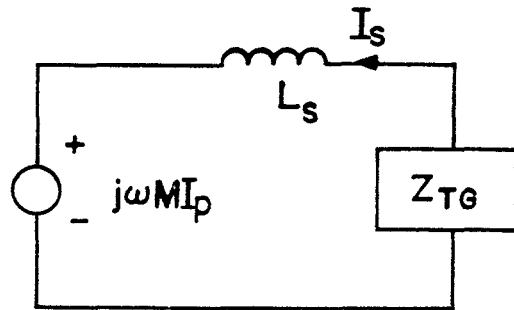
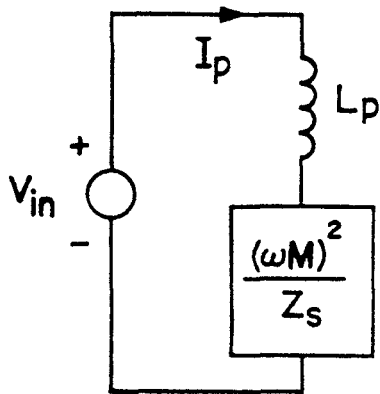


Fig. 1. Co-axial pulse transformer.



(a) Inductively coupled circuit.



(b) Equivalent primary circuit.

(c) Equivalent secondary circuit.

Fig. 2. Transformer circuit theory (Ref. 6, p149).

	$Z_{TG} = \infty$	$Z_{TG} = 0$
	Trigger gap has not broken down	Trigger gap has broken down
$ I_p $	$V_{in} / \omega L_p$	$V_{in} / \omega (L_p - \frac{M^2}{L_s})$
$ \frac{V_{out}}{V_{in}} $	M / L_p	0
$ \frac{\omega I_s}{V_{in}} $	0	$M / (L_p - \frac{M^2}{L_s})$

Table I. Variables of interest

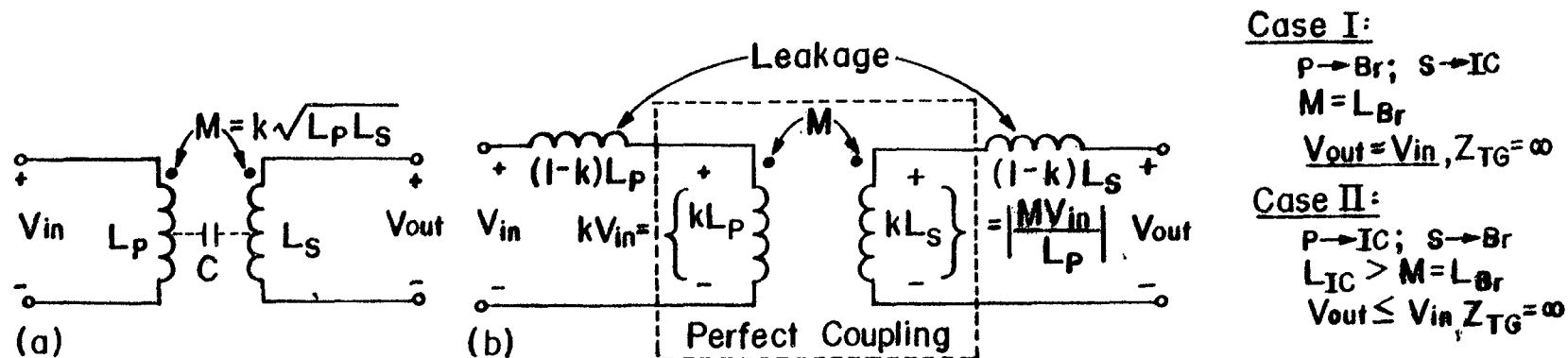


Fig. 3. Transformer circuits used in Table II. (Ref. 6, p151).

	D_{Br}/D_{IC}	D_{Br} (cm)	$L_{Br}(\mu H)$ Braid Inductance (Total)	k	M (μH) Mutual Inductance	$L_{IC}(\mu H)$ Inner Conductor Inductance	$ \omega I_s / V_{in} $ for $Z_{TG} = 0$		C(pf)
							Case I	Case II	
Single Turn Inner Conductor	1.33	2.14	2.10	0.950	2.07	2.25	4.41	1.33	≈ 310
	3.50	1.46	2.35	0.915	2.44	3.27	1.41	1.42	308
	6.35	1.46	2.34	0.847	2.45	3.59	1.03	1.03	218
	11.4	4.90	1.62	0.720	1.62	3.10	0.669	0.673	138
	21.3	4.90	1.65	0.688	1.65	3.50	1.17	0.225	122
Two Turns	3.50	1.46	2.35	0.873	4.70	12.4	0.654	0.667	308
	11.4	4.90	1.62	0.715	3.18	12.2	0.323	0.318	139

Table II. Measured transformer parameters.

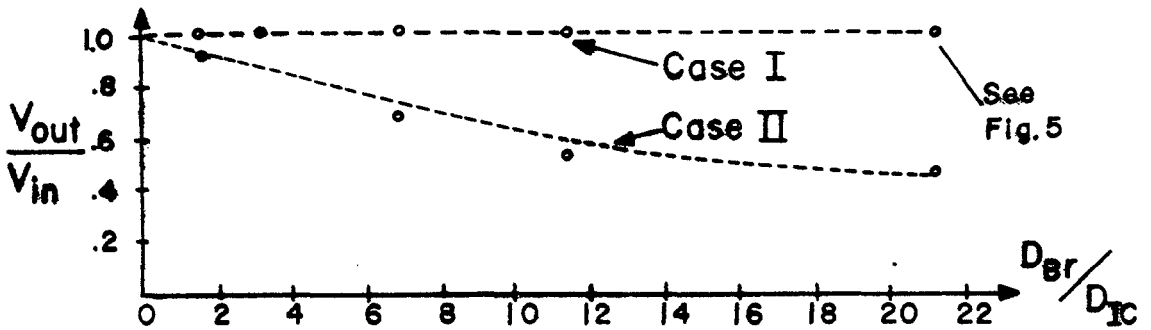
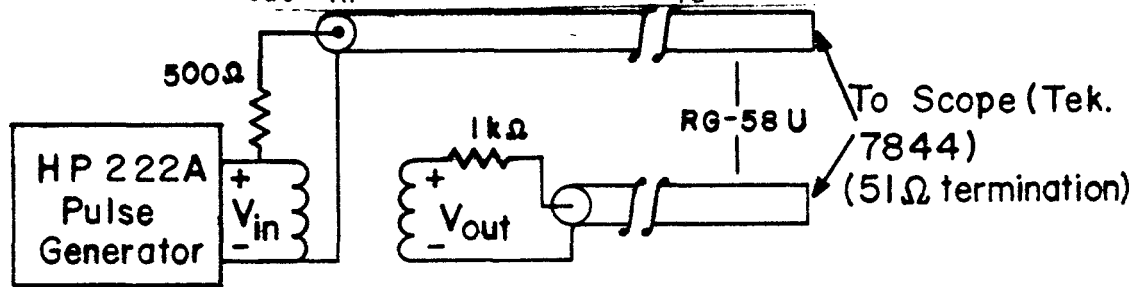
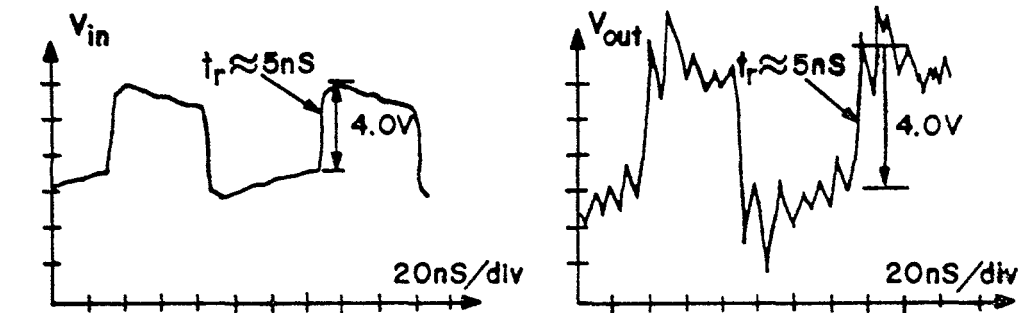


Fig. 4. V_{out}/V_{in} (at 140 kHz) with $Z_{TG} = \infty$, 1:1 transformer

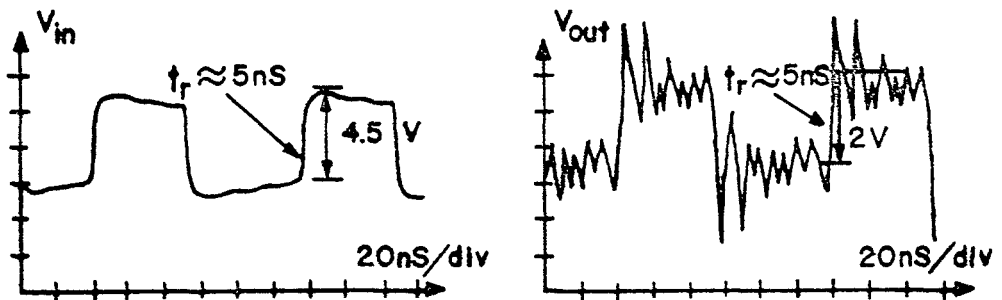


a) Test setup.

Case I



Case II



b) Typical results ($D_{gr}/D_{Ic} = 21.3$).

Fig. 5. Co-axial pulse transformer response to square wave input.